RESIDENTIAL HUMIDITY CONTROL: EXCITING NEW OPPORTUNITIES WITH AIR FLOW MODULATION

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ABSTRACT

This paper reviews psychrometric principles and shows how to formulate a psychrometric chart from a single equation. The chart is used to demonstrate the manner in which a conventional single-speed air conditioner adjusts its operating point in an attempt to control humidity over a range of conditions. The system performance with an electronically commutated motor (ECM) driving the blower is then presented.

With ECM blower speed control, it is possible to raise the sensible capacity, reduce the sensible capacity, and boost the efficiency of an otherwise conventional air conditioner. This makes such systems ideal to respond to the changing loads in a hot and humid climate.

INTRODUCTION

One of the major functions of an air conditioner is [illegible] review some of the basic principles of this process so that the full benefits may be made available in residential systems. These benefits have long been available in the more sophisticated, built-up systems used in large commercial and institutional applications. Various modulation schemes have been used selectively in these large systems for some time.

Capacity modulation of compressors in residential systems is coming. Two major manufacturers displayed variable speed systems at the ARI (Air Conditioning and Refrigeration Institute) Exhibition in New York City this past January. Capacity modulation of blowers is here. At least one major manufacturer is offering variable speed air handlers which can control humidity intelligently.

This paper reviews the psychrometric principles on which all air conditioners operate. Performance of typical single-speed air conditioners is examined in the framework of these principles. Then the exciting opportunity of air flow modulation is covered. The excitement flows from the fact that with an ECM (Electronically Commutated Motor) air handler, both the humidity control and the efficiency of a single-speed air conditioner can be improved. Finally, we'll take a quick look to the future . . . the fully modulated system.

PSYCHROMETRIC BACKGROUND

GENERAL

Psychrometry is the "branch of physics relating to the measurement or determination of atmospheric conditions, particularly regarding the moisture mixed with the air".[1] Understanding the psychrometric processes is essential to providing proper, total environment control of an air conditioner.

The psychrometric processes are usually portrayed on a psychrometric chart. The first charts were the result of work by Willis Carrier over 60 years ago. Since then, many variations of these charts have been produced by ASHRAE and major HVAC manufacturers.

The psychrometric charts relate six physical properties of moist air:

- Dry Bulb Temperature
- Wet Bulb Temperature
- Relative Humidity
- Dew Point (saturation temperature)
- Enthalpy (total heat content)
- [illegible]

Of these six, only two can be chosen independently. The remaining four are then totally determined by the two chosen. However, the exact relationships are rather complex. This is the motivation for use of the psychrometric chart. More recently, psychrometric routines on the desk-top computer have also been used.

THE PSYCHROMETRIC CHART

The Trane Psychrometric Chart is shown in Figure 1. This chart differs from most others through the incorporation of typical process lines. These lines run horizontally towards the saturation line. As they approach the 80 percent RH line, they bend downward and tend to become asymptotic at about 95 percent RH.

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[1] American Society of Heating, Refrigerating, and Air Conditioning Engineers, 1981 Fundamentals, Chapter 35.

Proceedings of the Fourth Symposium on Improving Building Systems in Hot and Humid Climates, Houston, TX, September 15-16, 1987

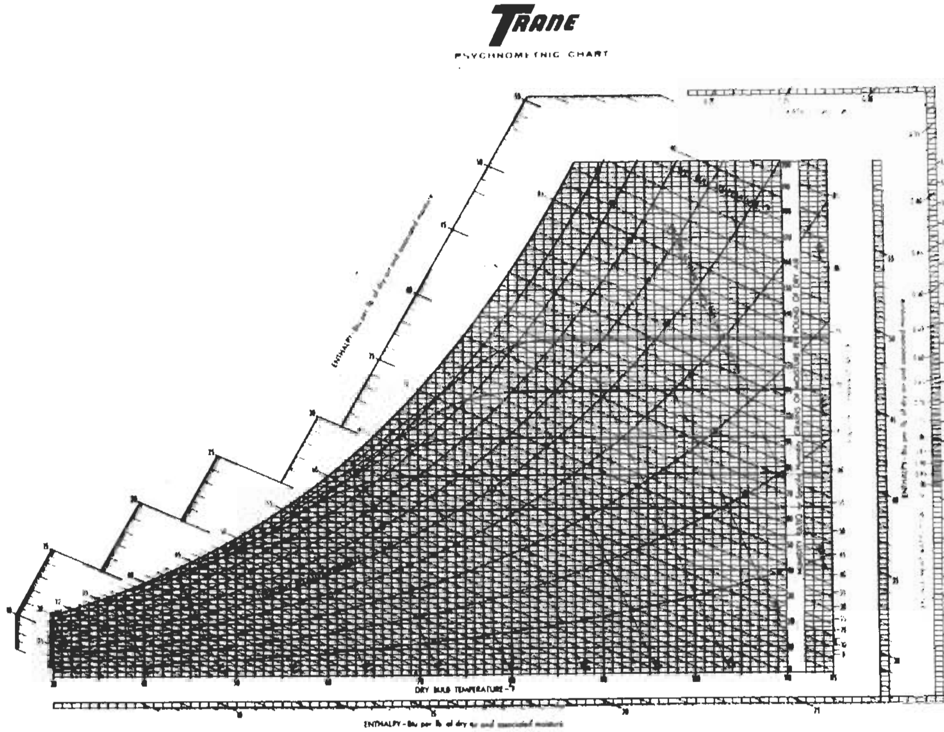

Fig. 1 Psychrometric Chart with Process Lines

An idealized cooling and dehumidification process would move from the air inlet condition (say at the bull's eye at 78°F and 50 percent RH) straight over to the saturation line, and then down this line to the air outlet (or supply) condition on the saturation line.

The departure from ideal, shown by the process lines on Figure 1, results from the fact that not all the air which passes through an evaporator coil actually contacts the chilled coil surfaces. Thus, the real process behaves as though most of the air followed the ideal path and a small portion of the air bypassed the coil, subsequently mixing with the air that took the ideal path. The greater the amount of effective bypass, the higher the temperature and the lower the RH at which the air will actually leave the unit.

SIMPLIFIED PC PSYCHROMETRIC CHART

In most cooling and dehumidification processes, the most important parameters of the air are the dry bulb temperature, the relative humidity and the water content of the air (grains of water vapor per pound of dry air). A chart relating these three parameters can be drawn from one approximating equation:

$$W_{SAT} = -17.62 + 16.2*EXP\ [0.0297*T] \qquad (1)$$

Where W_{SAT} = Humidity ratio of saturated air in grains of water vapor per pound of dry air

T = Temperature in degrees F

Purists might take exception with this simplified equation, and subsequent fractional scaling to get the relative humidity lines (i.e., W_{50} percent $\approx$ 0.5 x W_{SAT}). A sufficient defense would be that the errors are quite small. (Certainly, adequate for illustrative purposes, and probably for most engineering calculations).

Equation (1) was used in a spreadsheet to produce a table of W_{SAT} versus T and then to calculate W at 10 percent increments of relative humidity. These data were transferred to a plotting routine to produce the chart of Figure 2. This form of the chart facilitates adding process lines and rescaling for presentations or publication.

The resultant chart relates Humidity Ratio, Relative Humidity, Dry Bulb Temperature, and Dew Point. The dew point is not labeled, but is easily found. For example, at 75°F and 60 percent RH, W is 80 grains/#. Projecting downward from the saturation line at 80 grains/#, we find a temperature of about 60.5°F. This is the temperature at which air cooled from 75°F and 60 percent RH will condense, the so-called dew point.

TYPICAL PROCESS ON THE PC PSYCHROMETRIC CHART

An idealized, typical air conditioning process is shown on Figure 3. The air enters the unit at 80°F and 50 percent RH and leaves the air conditioner at about 58°F and 86 percent RH. When leaving air conditions are known, it is more common to simply draw a straight line between these two points as will be illustrated later.

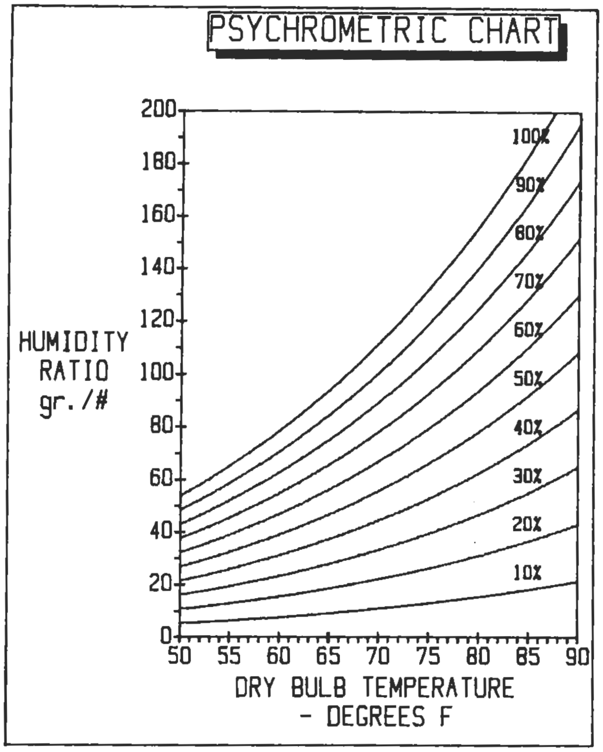

Fig. 2. PC Psychrometric Chart

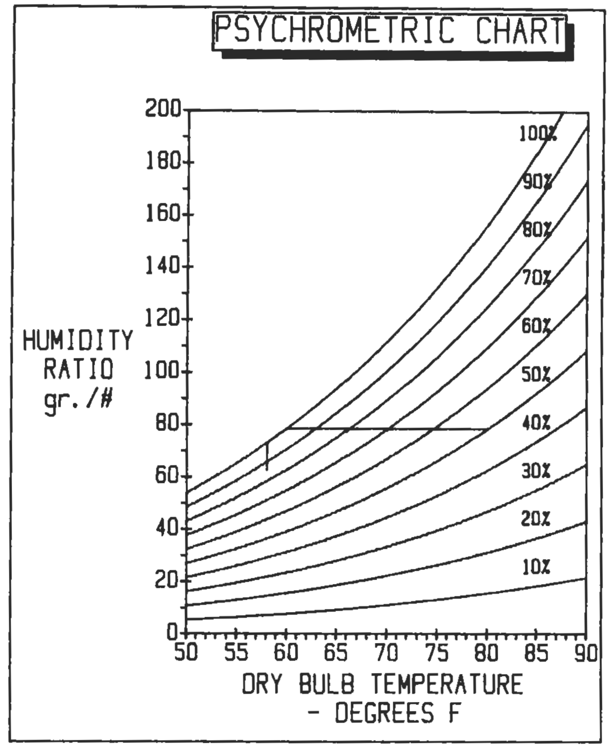

Fig. 3 Idealized Cooling Process

A more accurate representation of the process line would be the form of the process lines in Figure 1. A single straight line between the end points is often used because the driving concern is the psychrometric conditions entering and leaving the apparatus.

A note of caution is appropriate. Although process lines of the form shown on Figure 3 are of value, no simple air conditioning process can follow the implicit steps shown. The short vertical line at 58°F implies removal of moisture with no change in temperature. No known process can do so. Regardless, the incremental process implementation implied by the diagram is a useful tool for discussion.

ONE-SPEED SYSTEMS: VIRTUAL FEEDBACK CONTROL

CAPACITY VERSUS LOAD

The conventional one-speed system is a remarkable machine. It not only works against the forces of nature by transporting heat from cool to hot places, it also has a natural tendency to shift its characteristics in response to the load. This is shown in Figure 4. The left-hand diagram shows the total capacity in thousands of BTU/Hr; the middle diagram shows the sensible capacity; and the right-hand diagram shows the latent capacity. Latent capacity is the measure of a system's ability to remove the latent heat of the water vapor (i.e., to condense and remove water vapor from the air).

Dew point rather than relative humidity was chosen as the abscissa on the diagrams because it is a measure of the total moisture content of the air.

In the left-hand diagram, we see that the air conditioning system capacity to cool and dehumidify increases as the entering room air becomes hotter and wetter (higher dew point). This is a characteristic of the basic air conditioner, not any sophisticated control.

Interpretation of the middle and right-hand diagrams is a bit trickier because they should be viewed together. The trends we see are that:

- With constant dew point,
  - Sensible capacity increases with increasing room temperature, and
  - Latent capacity decreases with increasing room temperature.
- With constant temperature,
  - Sensible capacity decreases with increasing room dew point, and
  - Latent capacity increases with dew point.

These observations can be quantified using approximate equations:

$$H_T = H_L + H_S \qquad (2)$$

$$H_L = 0.68 * CFM * \Delta W \qquad (3)$$

$$H_S = 1.08 * CFM * \Delta T \qquad (4)$$

Where

H_T = Total Capacity, BTU/Hr.

H_L = Latent Capacity, BTU/Hr.

H_S = Sensible Capacity, BTU/Hr.

CFM = Air flow through the evaporator coil, 1200 in this case.

ΔW = Difference between grains of water vapor per pound of dry air at the inlet and outlet.

ΔT = Difference between dry bulb temperatures at the inlet and outlet.

Using line 4-8 as an example,

W_4 = 99.67 grains/# $\qquad T_4$ = 80°F

W_8 = 78.25 grains/# $\qquad T_8$ = 62.5°F

$$H_T = H_S + H_L = 17.7 \text{ KBTUH} + 22.7 \text{ KBTUH} \qquad (5)$$
$$= 40.4 \text{ KBTUH}$$ (within 2 percent of the published value)

VIRTUAL CONTROL-POINT OFFSET: THE PIPER'S PAYCHECK

The virtual feedback control of the environment by an air conditioner as described above has a catch. Like many actual feedback control systems, a change in load requires a control point error or offset in order to shift the system to a new, more desirable, operating state.

As an example, suppose the system is operating at 50 percent duty cycle (percent of "on" time) and the room conditions are a comfortable 75°F and 45 percent RH. Introduce a large increase in latent load (an atomizing vaporizer will do for this example). As the humidity increases, the latent capacity will increase, the sensible capacity will decrease, and the duty cycle will increase to offset the lost sensible capacity.

While it is possible in theory for the system to balance out again at 75°F and 45 percent RH, it is most unlikely. The more general trend will be that the relative humidity will drift upward.

If the system were running at 100 percent duty cycle, this would be very evident, since both the humidity and temperature would drift upward.

Under thermostat control at lower duty cycles, the system will maintain the original dry bulb temperature of 75°F. How far the relative humidity will drift depends on the magnitude of the added latent load and the specific characteristics of the air conditioner.

Regardless, the general condition is that the relative humidity will drift upward. Just as higher relative humidity causes a shift to more latent capacity, achieving that shift normally is associated with higher humidity. The piper will be paid.

AIR FLOW MODULATION: THE TRANSITIONAL SYSTEM

CONVENTIONAL

Air flow modulation has been used with large, single-speed systems for many years. With air flow modulation, the operating point of a system can be shifted "simply" by adjusting the speed of the indoor blower (i.e., the air flow through evaporator coil).

In the early days, speed modulation was done by changing pulleys, or changing the setting of an adjustable pulley. This could be done on both commercial and residential systems. In both cases, the adjustments were made infrequently due to the time and inconvenience.

More recently, commercial systems have relied on adjustable pulleys (which can be adjusted remotely as they run), eddy current drives, or inverter-driven induction motors. These technologies have all been too expensive for residential systems, which have tended to use tapped induction motors, with only seasonal air flow changes.

The tapped induction motor has a rather narrow range of speed adjustment, and downward modulation is quite inefficient. In fact, it is so inefficient that most systems decrease in efficiency as the air flow is modulated downward. For residential systems, a more efficient form of downward air flow modulation is needed.

ECM (ELECTRONICALLY COMMUTATED [PERMANENT MAGNET] MOTOR)

Air handlers and furnaces are now available with ECM motors. These motors permit rather simple, and very efficient, changes in blower speed. Coupled with a humidistat, this equipment provides some rather dramatic air conditioner control opportunities.

Recent psychrometric tests of an air conditioner with an ECM air handler gave the results shown in Figure 6. These data were taken on a 3 1/2-ton unit at the ARI rating point of 82°F outdoors and 80°F dry bulb and 67°F wet bulb indoors (about 52 percent RH).

The left-hand view shows absolute values of sensible and latent capacity as a function of air flow, and the right-hand view shows values relative to the base case (maximum air flow). We see that reduced air flow can give a 20 percent increase in latent capacity along with a 13 percent reduction in sensible capacity (at 900 cfm . . . about 300 cfm/ton). The ratio of latent to sensible capacity can be enriched even more by further reductions in air flow. These shifts are in addition to those that were discussed above when the room air conditions were permitted to drift.

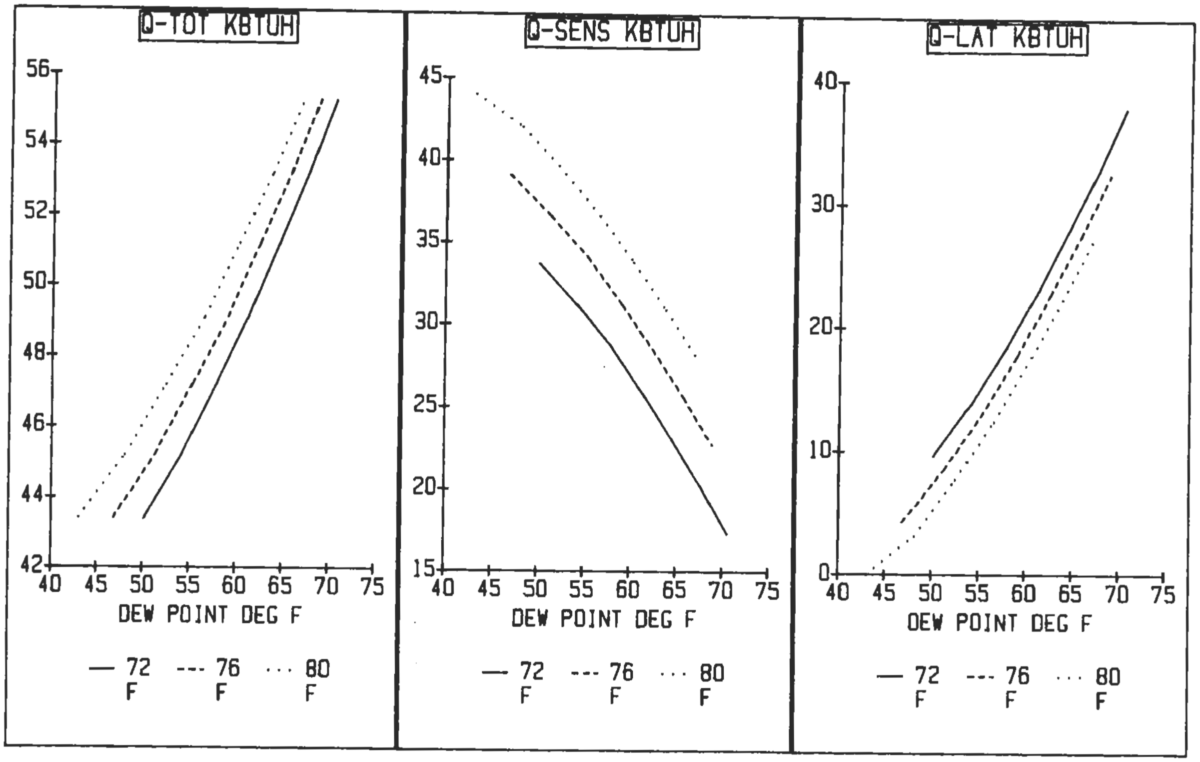

Fig. 4 A Typical One-Speed Air Conditioner at 75°F Outdoors

This is a rather remarkable example of the laws of physics working in all the right directions to maximize comfort. The net effect is a form of virtual feedback control in which the system responds to the room conditions (air entering the air conditioner) in such a way as to increase its capacity to cool and dehumidify as the air becomes warmer and more humid.

PERFORMANCE ON A PSYCHROMETRIC CHART

A different perspective of one-speed systems is given in Figure 5. The four lines on the figure represent the effective process lines for the system with inlet wet bulb temperatures of 59, 63, 67, and 71°F (i.e., line 1-5 is at 59°F TWB, etc.).

The differences in the coordinates of the end points on each line can be used to determine the sensible and latent capacity. Line 1-5 is horizontal, representing a dry-coil condition with no dehumidification. Line 4-8 represents a reduction in sensible capacity and an increase in latent capacity.

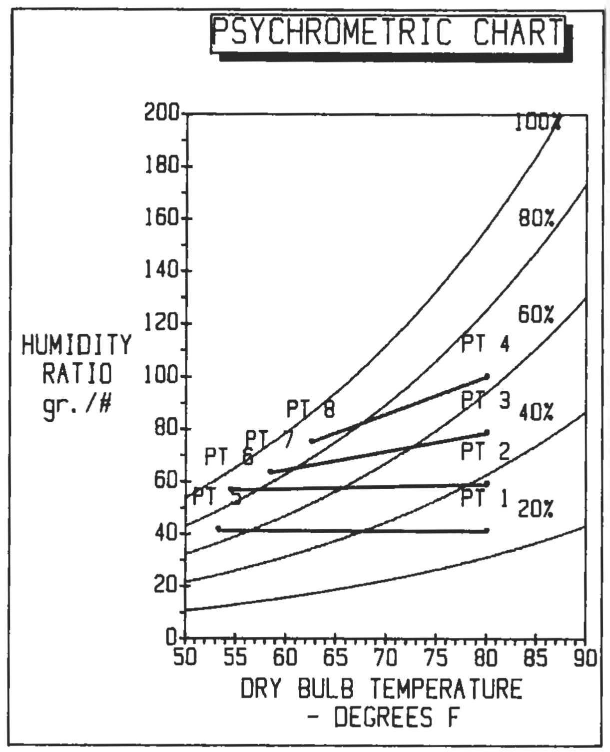

Fig. 5 Effect of Inlet Conditions on a One-Speed Air Conditioner at 85°F Outdoors

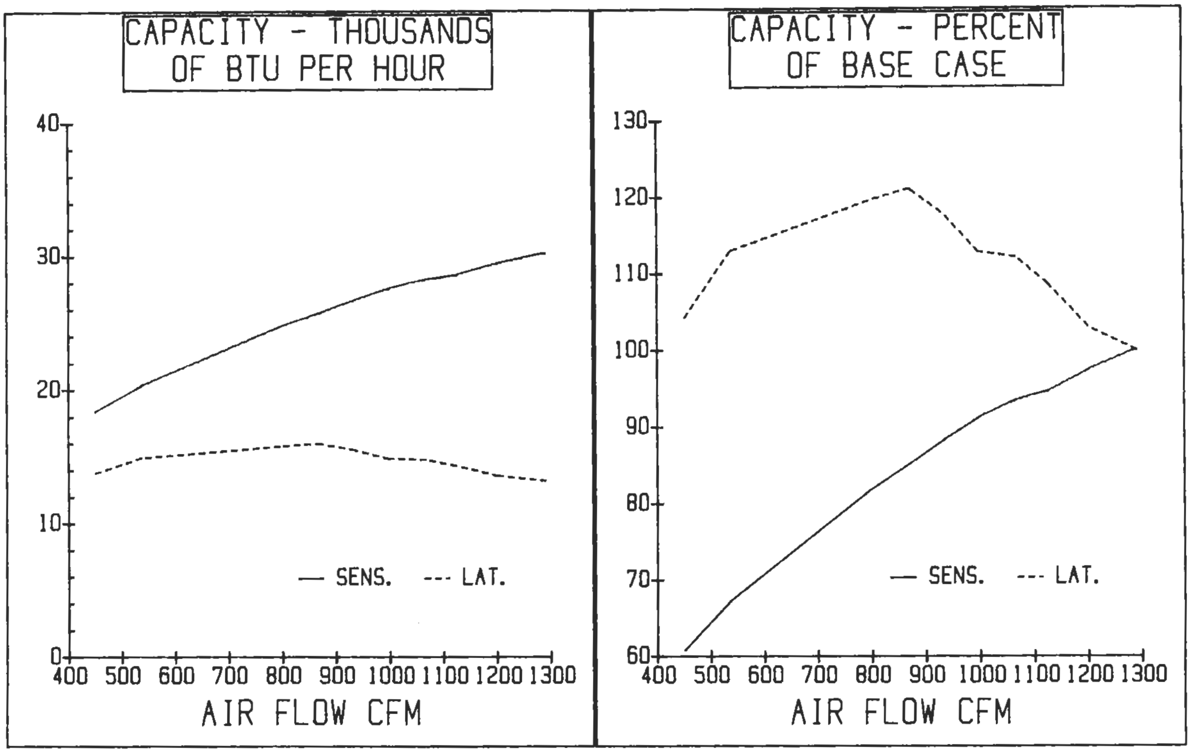

Fig. 6 Performance of a One-Speed Air Conditioner with an ECM Air Handler

WHAT ABOUT ECM EFFICIENCY?

The efficiency trend shown in Figure 7 is the real surprise. As the air flow is reduced from 1290 cfm to 934 cfm, the system efficiency increases by about 4 percent! The key to this increase is the high efficiency of ECM. Over the normal operating range, this ECM almost follows the perfect cubic law of power input required for a given air flow.

A side note on efficiency is in order. Conventional wisdom today is arguing that high efficiency systems provide poor humidity control. The ECM example, based on real hardware tests, proves that you can have good humidity control and high efficiency.

At worst, this system has over 30 percent of its capacity (at 82/80-67) in the form of latent capacity. As air flow is reduced to give maximum efficiency, the latent fraction increases to about 43 percent.

FULLY MODULATED SYSTEMS

The generation of the fully modulated, variable speed system is just emerging. These systems will provide total system control . . . tailored to match the instantaneous load.

With the variable speed system, the compressor and blower can both be modulated to permit total environment control. The system will permit the occupant to enjoy the exact environment he selects. Humidity and temperature can be controlled independently as long as there is a need for cooling.

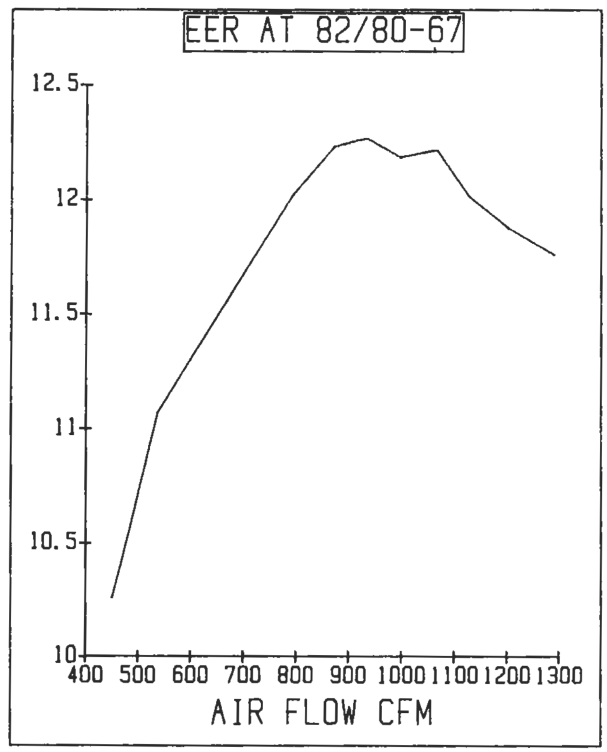

Fig. 7 Efficiency Versus Air Flow for a One-Speed Air Conditioner with an ECM Air Handler

Proceedings of the Fourth Symposium on Improving Building Systems in Hot and Humid Climates, Houston, TX, September 15-16, 1987

CONCLUSION

These are exciting days in the HVAC field, particularly for those of us who live in the hot and humid climates.

The conventional air conditioner has served us well, in part due to its intrinsic tendency to provide more dehumidification when more was needed. Under very humid conditions, it may not have provided enough for true comfort. In the past, we've made things tolerable by reducing room temperature to offset the adverse effects of higher humidity . . . and the experts have told us that we were as comfortable as if we had the conditions we really sought.

The days of fully modulated systems are fast approaching. These systems will be able to be controlled so that the sensible and latent capacity can be modulated to match the load . . . and without cycling "on" and "off" during most of the season.

In the interim, we have the ECM air handler for use with conventional single-speed outdoor units. Although the systems will still cycle "on" and "off", the air flow can be modulated to adjust the latent/sensible capacity split to exactly match the load over a wide range of conditions. The easiest way to do this with conventional control hardware is to use a humidistat to switch the blower between two speeds.

Air flow modulation is being done so efficiently that we can boost system efficiency at the same time as we increase latent capacity. ECM really demonstrates that, through technology, efficiency and comfort are in harmony.